Bootstrapping a Trustworthy and Seamless Digital Engineering System

Ph.D. Preliminary Exam

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April 17, 2023

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Outline

→ James S. Wheaton

- B.S. Mechanical Engineering, Purdue University (2011)
- Former software engineer and consultant in ecommerce, big data, and blockchain
- Started Systems Engineering Ph.D. @ CSU in 2017, part-time remote
- Completing coursework Spring 2023 in the 72-credit-hour Ph.D. degree program
- Computer hobbyist since age 5
- Likes to study programming languages of all kinds
- Builds all software from source with hardened toolchains, whereever possible

① Introduction

→ Digital Engineering Is an Integration Challenge

Digital Engineering currently relies on *interoperability* as the primary mechanism for constructing the Authoritative Source of Truth, e.g. with APIs and format interchange standards[1].

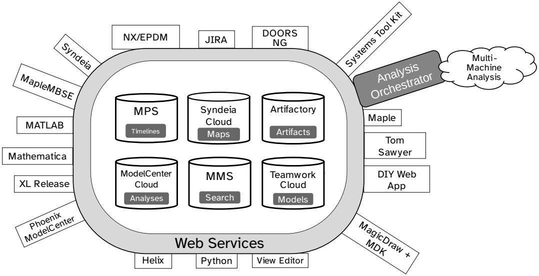


Figure: Depiction of NASA JPL OpenCAE Environment (Adapted from Delp 2019)

[1] Bajaj, Friedenthal, and Seidewitz 2022

→ We Build Our Computer Systems Like Cities

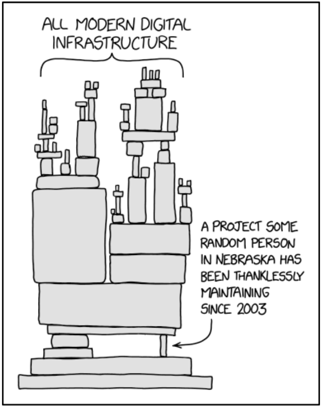


Figure: xkcd: Dependency (Munroe 2020)

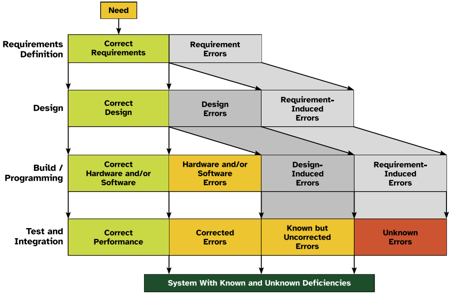


Figure: The Error Avalanche (Adapted from Claxton, Cavoli, and C. Johnson 2005)

→ Cybersecurity is a “Mess” or Wicked Problem

US CISA Director has recently highlighted a *“normalization of deviance”* in the computing industry and called on vendors to provide systems that are **secure-by-default** and **secure-by-design**.[1] The situation is untenable:

- Pervasive use of memory-unsafe languages, including in OS, compilers, security-critical components and theorem provers[2]
- Common Vulnerabilities and Exposures are on the rise
- CPU microarchitecture side-channel vulnerabilities are unpatchable[3]
- Internet architecture vulnerabilities & protocol ossification[4]
- Trusting Trust attack remains ignored after 50 years[5]
- Cyber-infrastructure is inherently insecure [6]

[1] Easterly 2023 [2] Chisnall 2018; Du, Wu, and Mao 2023; Winterer, Zhang, and Su 2020; Bringolf, Winterer, and Su 2022 [3] Porras and Lindell 1995; Lipp et al. 2020; Kocher et al. 2020; Schwarz, Weiser, Gruss, et al. 2017; Van Bulck et al. 2018; Weisse et al. 2018; Schwarz, Weiser, and Gruss 2019; Skarlatos et al. 2019; Murdock et al. 2020; Schaik, Minkin, et al. 2021; Schaik, Kwong, et al. 2020; Borrello et al. 2022 [4] Ammar 2018; Papastergiou et al. 2016 [5] Karger and Schell 2002; Thompson 1984; Wheeler 2009 [6] Massacci, Jaeger, and Peisert 2021; Smith and Mulrain 2018; Dawson et al. 2021; Algarni 2021; Hobbs 2021

Digital Engineering Has a Reverse Salient

The *reverse salient* is a **set of critical problems**[1] whereby system components "fail to deliver the necessary level of technological performance thereby inhibiting the performance delivery of the system as a whole":[2]

- WIMP applications paradigm — essential functions are outsourced
- false dichotomy of user / developer
- inscrutable binary executable vs. sprawling source code
- physical centralization + lack of isolation, e.g. CPU
- sequential-first processing, e.g. CPU
- lack of integrated program documentation, test, and verification facilities
- plethora of ill-defined languages/formats
- security-by-obscurity

[1] Hughes 1993 [2] Dedehayir and Mäkineif 2008

→ Looking for the Escape Hatch

The systemic problem of trustworthy cyber-systems has been known for 25 years.[1]
Recent research efforts have attacked the mess from different perspectives:

- Fully Countering Trusting Trust through Diverse Double-Compiling[2]
- DARPA Cyber-Assured Systems Engineering (CASE)[3]
- DARPA Clean-slate design of Resilient, Adapative, Secure Hosts (CRASH)[4]
- DARPA META-II[5]
- DARPA Circuit Realization At Faster Timescales (CRAFT)[6]
- Deep Specification[7]
- Formally-verified stack from assembly language to CPU[8]

[1] McLean 1997; Council et al. 1999; Mundie et al. 2002; Spafford 2004 [2] Wheeler 2009 [3] Cofer 2021 [4] *Clean-slate design of Resilient, Adapative, Secure Hosts (CRASH)* 2010; Chiricescu et al. 2013 [5] *META-II* 2010 [6] *Circuit Realization At Faster Timescales (CRAFT)* 2015 [7] Appel et al. 2017 [8] Moore 2003; Moore 2007

→ Research Questions

RQ1 What are the gaps, barriers and cost drivers of engineering provably-correct cyber-systems?

RQ2 Can these gaps be adequately addressed with today's computing ecosystem?

RQ3 What would a clean-slate digital engineering system that addresses the gaps and barriers look like?

RQ4 Can we prove that such an architecture is seamless and trustworthy?

②

Operational Concept of Clean-slate DE System

→ DE Meta-Model

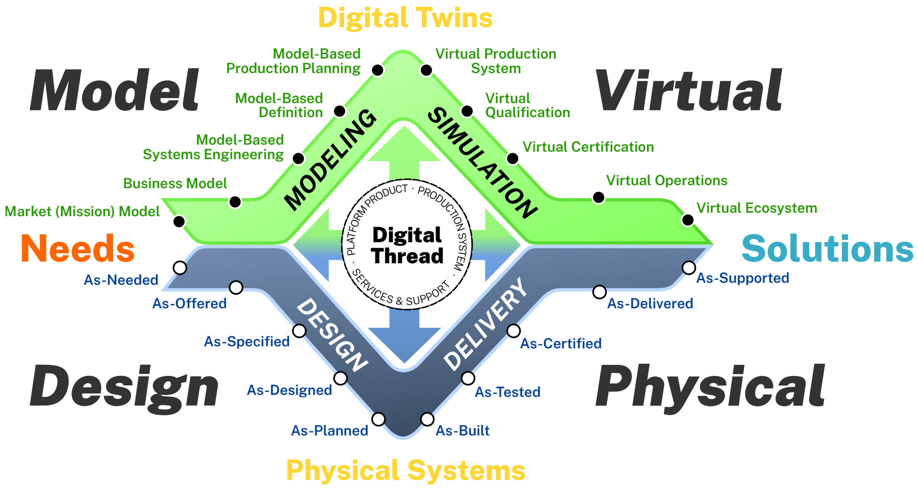


Figure: The Boeing MBSE Diamond: Continuity of the system's 'Digital Thread' (Adapted from Seal 2018)

→ DE Essential Functionality

DE practitioners need a predictable set of affordances for doing their work:

- *Mathematics:* matrices, equation solving, calculus, optimization, probability and statistics, discrete math, theorem proving
- *Science:* physical constants & models, simulations, experimental design, properties of matter
- *Engineering:* 3D geometry, finite-element analysis, fluid dynamics, thermodynamics, materials, reliability, systems modeling, units
- *Knowledge Engineering:* ontologies, authoritative data, rich media, process meta-models, query capabilities
- *Project & Program Management:* PERT, critical path method, EVM, Gantt charts, project economics and accounting

→ Human-Computer Interaction

We need to re-think HCI for human factors:

- WIMP breaks down at scale
- Applications enforce costly context switches, data incommensurability
- Everything-is-an-object with Capabilities is a simpler formalism
- Coherence of textual & graphical representations aids efficient, diverse uses
- Localization and accessibility must be designed-in from the beginning
- AI augmentation is an option, powerful in some contexts

→ Quality Attributes

- **seamless:** consistent and coherent interfaces throughout
- **trustworthy:** provenance of components is known, auditable and traceable; components reliably implement their specifications and carry proof certificates
- **elegant:** "a system that is robust in application, fully meeting specified and adumbrated intent, is well-structured, and is graceful in operation"[1]
  - efficacy
  - efficiency
  - robustness
  - minimizing unintended consequences
- **convivial:** serve the operator and their community for creative and autonomous use, with the power to develop mastery[2]

[1] M. D. Watson, Mesmer, and P. Farrington 2019; M. Watson, Mesmer, and P. Farrington 2020; Madni 2012; M. D. Watson, Griffin, et al. 2014; M. D. Watson 2017 [2] Voinea 2018

③

Theory Development

→ Understanding Tool Integration

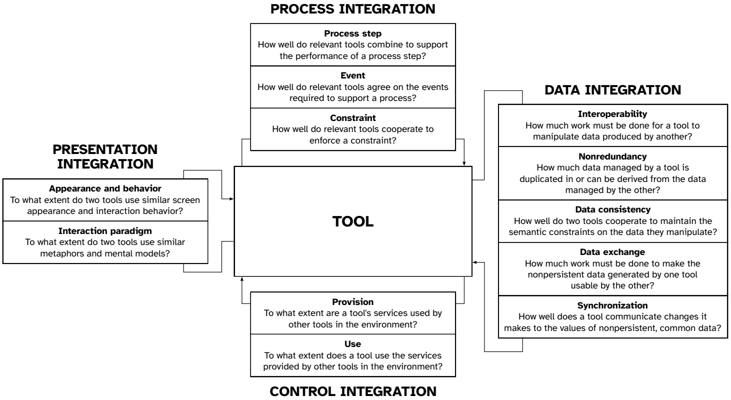


Figure: Tool Integration Entity-Relationship Diagram (Adapted from Thomas and Nejmeh 1992)

→ LISP the Meta-Language

Language-oriented programming has "advantages for domain analysis, rapid prototyping, maintenance, portability, user-enhanceable systems, reuse of development work, while also providing high development productivity" [1]

One of the guidelines of language-oriented programming is that it "enables creators of languages to enforce its variants. ...When a program consists of pieces of different languages, values flow from one context into another and need protection from operations that might violate their integrity."[2]

Programming paradigms depending on need: imperative, functional/declarative, symbolic, constraint/logic, array and stack, dataflow, query, metaprogramming. Gradual typing supports different phases of the system development lifecycle.

[1] Ward 1994 [2] Felleisen et al. 2018

→ Defining Seamless Architecture

- Are Interfaces everywhere fully defined and satisfied at every connection endpoint (Port)?
- Do Parts refine their imported types?
- Do Part Specifications prove out Ports are derivations of internal Parts and `in` Ports and Item Flows?
- Disparate interfaces are not exposed to the operator (“islands of functionality”)

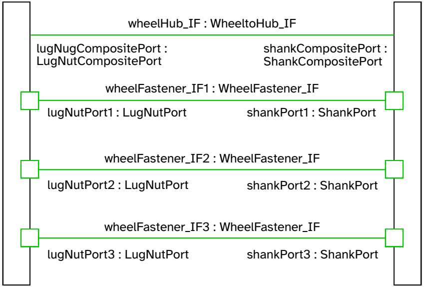


Figure: Interfaces in SysML v2 demonstrating seamlessness (Adapted from Friedenthal 2023)

→ Defining Trustworthy

Trustworthiness is a Quality Attribute related to reliability and security, and based on a set of measurable factors:

- Behavior is well-defined
- Side-channels are explicitly guarded where feasible
- Object Capabilities are ubiquitous for fine-grained security[1]
- Components carry proof certificates, with traceability
- System must be independently verifiable against their specifications
- Bootstrappable, defended against Trusting Trust attacks

[1] Rees 1995; Richardson, Carey, and Schuh 1993

→ Sketching the Bootstrap Process

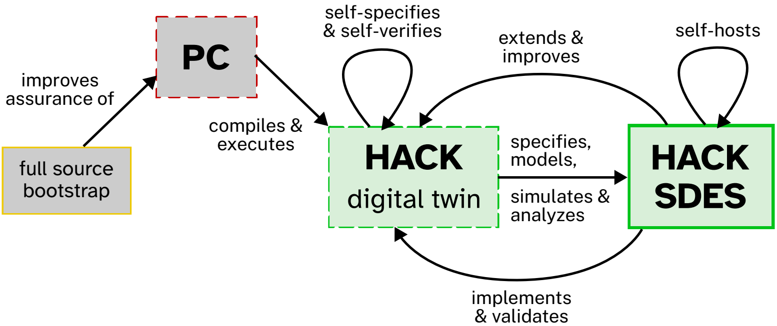


Figure: Simplified view of HACK bootstrap process

→ Formal Proof Strategy

Goal: A trustworthy system is constructible from untrustworthy components.[1]

- Untrustworthy components are diverse
- Untrustworthy components produce the same output for a given input
- Trustworthy components carry proof certificates
- Trustworthy components are auditable
- Untrustworthy components are replaceable by trustworthy components
- Trustworthy system has an independently-verifiable root-of-trust

Build from Wheeler 2009's Diverse Double-Compiling formal proof to include more of the system components.

[1] Rajendran, Sinanoglu, and Karri 2016; Cui et al. 2022; Sethumadhavan et al. 2015

④

Design of High-Assurance Computing Kit

→ HACK Specification Tree

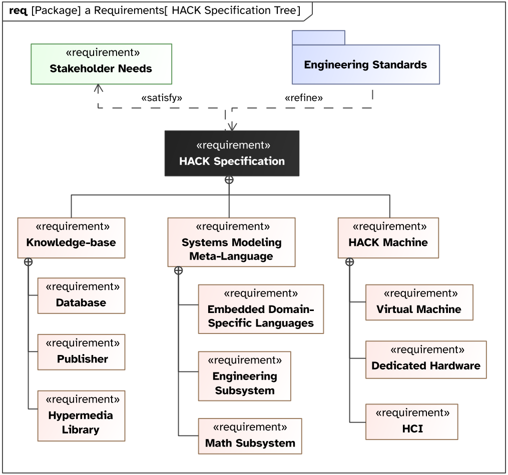
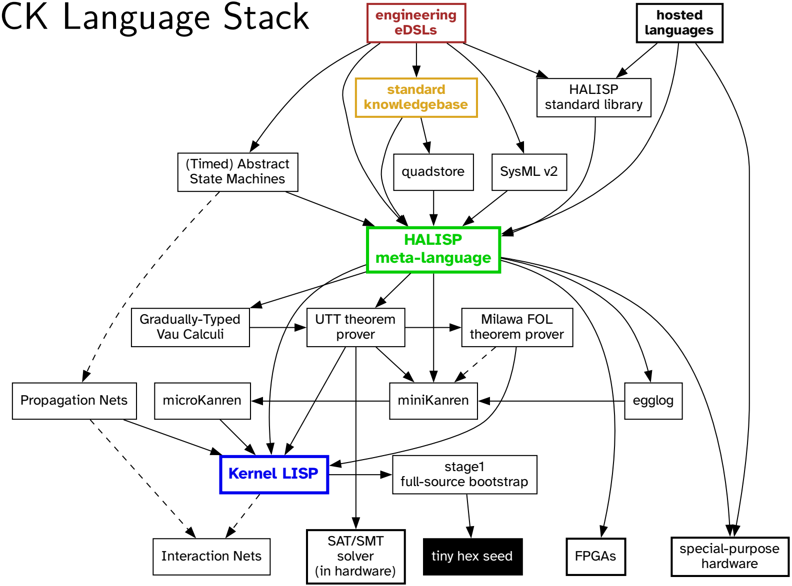


Figure: HACK Specification Tree

→ HACK Language Stack



→ HALISP Language Design

```
(def:function hello-world   ;; name of the pure function
  :doc       (document "A complete DocBook object or AsciiDoc string")
  :type      [ String :-> String ]
  :params    [ name ]
  :requires  [(> (length name) 0)]
  :ensures   (= (length out)  ;; Hoare triple post-condition
                (+ (length "Hello, ")
                   (length name)
                   (length "!")))
  :satisfies [ :FR/001 ]    ;; SysML Block "satisfies" Relationship
  :tests      [(test trivial-example
                 :doc "Test that the name is inserted into the greeting."
                 :verifies [ :FR/009 ]  ;; SysML Functional Requirement
                 (= "Hello, World!"
                    (hello-world "World")))
               (ref:test :T/HW-002)]
  :version   { :major 0 :minor 1 :patch 0 })  ;; enforceable semantic versioning

;; Separation of specification and implementation
(def:function-body hello-world
  (str "Hello, " name "!"))  ;; function body usually starts on a newline
```

Figure: HALISP integrates formal verification, systems eng. & project mgmt.

→ HACK HCI (1)

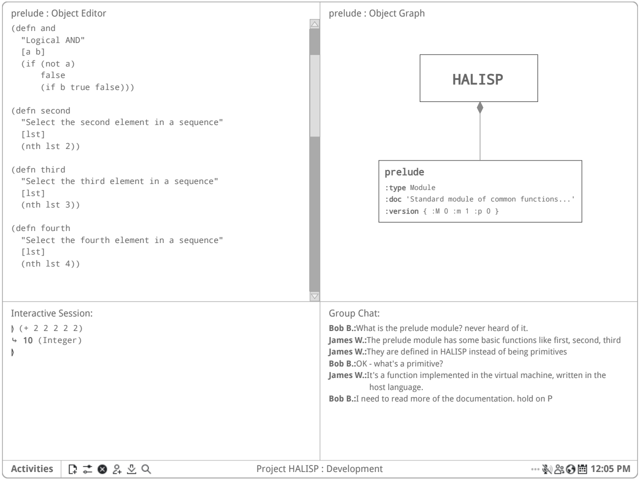


Figure: Team collaboration with text/voice chat and screenshare is built-in

→ HACK HCI (2)

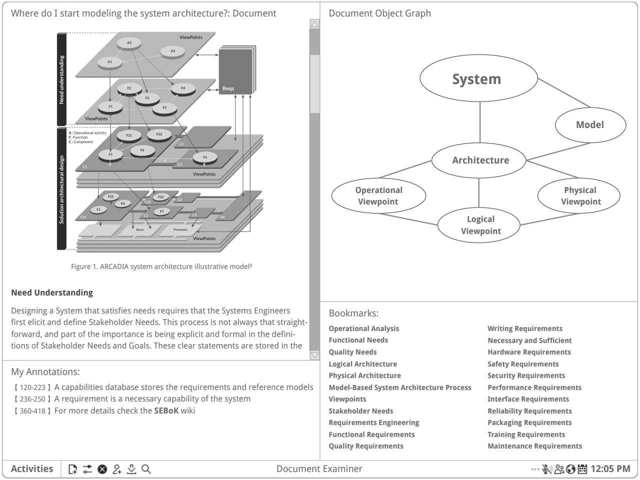


Figure: Knowledgebase is browseable, annotatable, with transclusion & object graph views

→ HACK HCI (3)

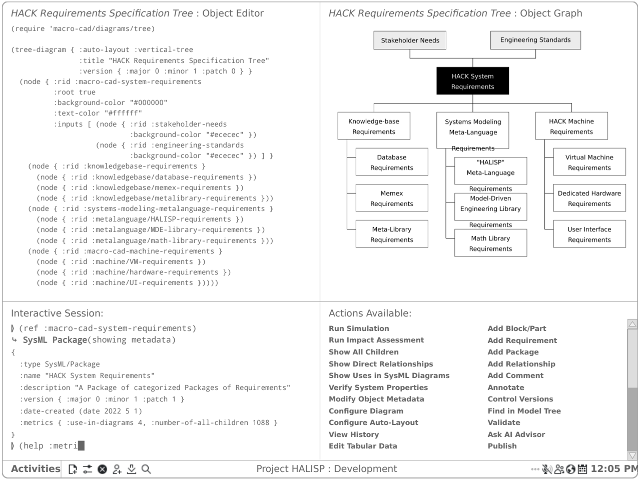


Figure: Textual and graphical representations are coherent; interactive programming session; contextual actions are listed

→ HACK Prototype

The HACK prototype is being developed with the capabilities to model the HACK system. Current functionality is testing the LISP meta-language approach:

- Small LISP implementation with REPL in Ada 2012
- Programmable graphics with SVG for diagrams and presentation slides
- Use of DocBook standard to define systems engineering document templates
- Website generation from given templates and source files
- SysML and project definitions
- Knowledgebase entry definitions

5

Summary & Research Plan

→ A Grand Challenge in Systems Engineering

- Digital Engineering requires a **Transdisciplinary Systems Engineering** approach![1]
- We need the right framing and goal to build support
- End-to-end formal verification enables certification of system and components' correctness so they can be deemed *finished* or safely refactored

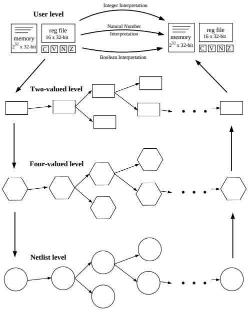


Figure: The FM9001 gate-level model corresponds to the high-level functional model (Moore 2003; Moore 2007)

[1] Mesmer et al. 2022

→ Research Contributions

1. Operational concept of a trustworthy & seamless digital engineering system
2. Formal definitions of ‘trustworthy’ and ‘seamless’ within this context
3. Formal proof of soundness of the approach of bootstrapping a trustworthy system from untrustworthy components
4. An open-source SysML v2 model of the proposed system architecture with prototype for demonstrating key functionality

→ Papers In-Progress

1. "Seamless Digital Engineering: Motivating a Grand Challenge"
   - *80% complete*
   - **Target conference:** INCOSE Western States Regional Conference 2023
2. "Digital Engineering Modeling Languages as LISP-Embedded Domain-Specific Languages"
   - *20% complete*
   - **Target conference:** INCOSE Western States Regional Conference 2023
3. "Architecture Essentials of a Seamless Digital Engineering System"
   - *50% complete*
   - **Target conference:** INCOSE IS 2024

Timeline to Completion

Summer 2023 JPL internship at half-time; continue HACK architecture modeling and prototype development; theory development, setup and testing of formal definitions and proofs; notification of acceptance for 2 conference papers

Fall 2023 Develop proofs, test and interpret results; architecture model completeness assessment; attend conference, and submit 1-2 papers to INCOSE IS conference or SE journal

Spring 2024 Final editing and presentation of results in dissertation; defense and graduation planned near end of semester

→ Future Work

- Continue architecture design and prototyping
- Reference model and reference architecture of DE lifecycle with product-line architecture instantiations for particular types of systems
- Computational type theory view and investigations of system architecture building from SysML v2 semantics
- Proving an architecture seamless and trustworthy at the type level
- Analysis of system bootstrap paths, size and effort
- Comparison and type-level analysis of extant computer system architectures
- Working out details of computational design of HACK systems
- Characterize ‘architectural ossification’ or intransigence

→ Thank you!

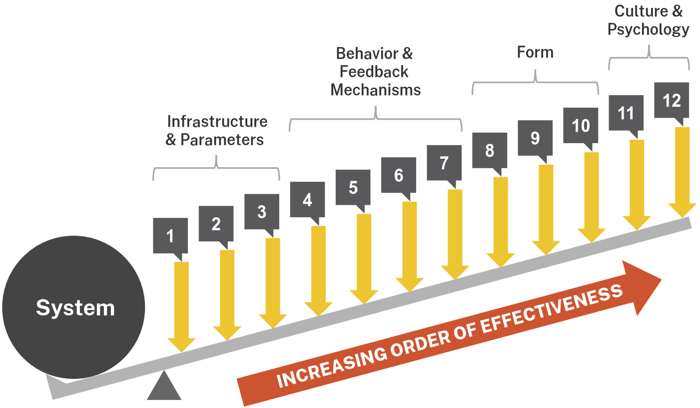


Figure: Places to intervene in a system (Adapted from Meadows 2008)

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